Tropospheric Emission Spectrometer (TES) CO_2 for carbon cycle science

Susan Kulawik, Dylan Jones, Ray Nassar, John Worden, F.W. Irion, Kevin Bowman, and the TES team

Why measure CO_2

Remote sensing of CO_2

Results from TES

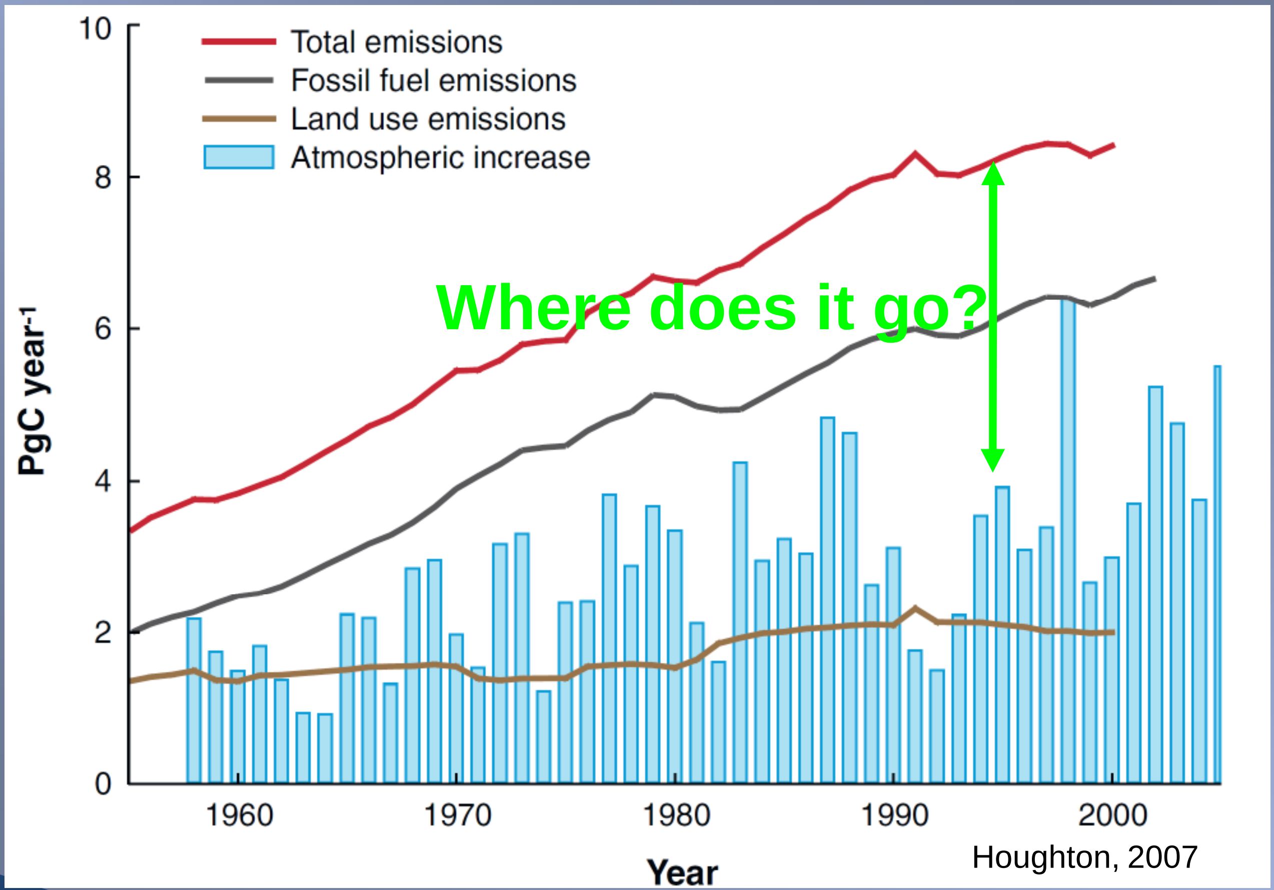
Averaging for source & sink estimates

The missing sink(s)

Carbon dioxide is the most important anthropogenic greenhouse gas

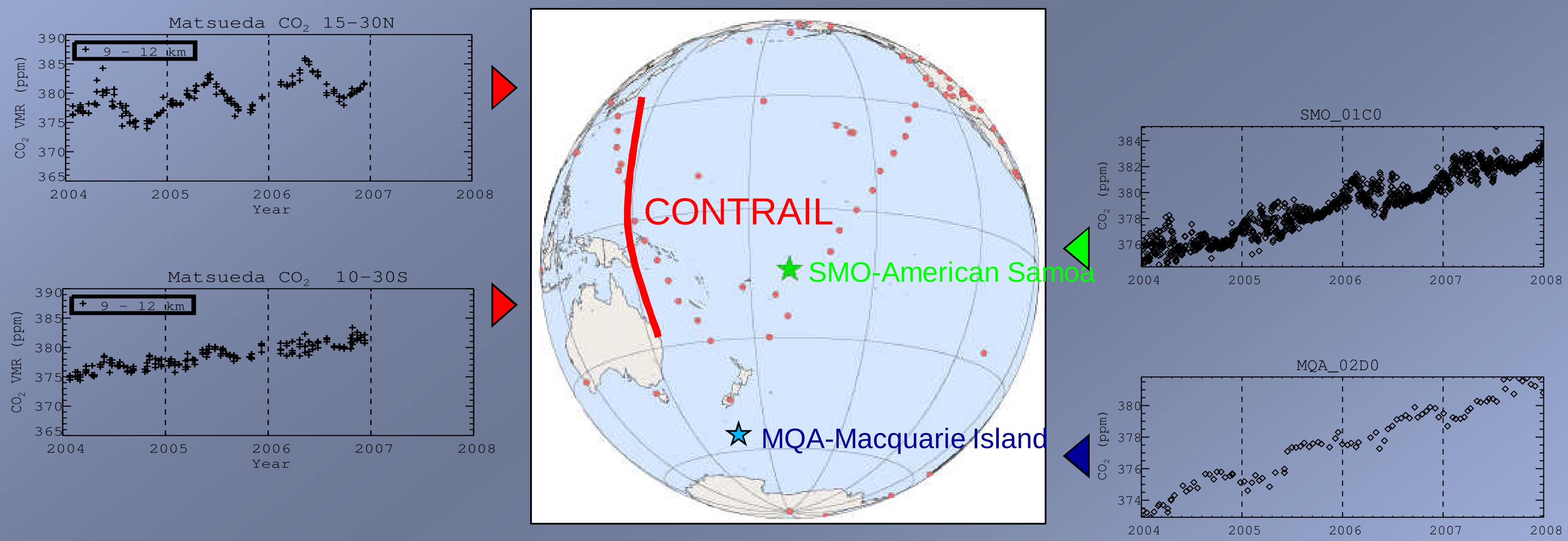
Only 50% of emissions remain in the atmosphere

Understand carbon cycle to understand fluxes and mitigate warming(?)



Global and seasonal variations

Although CO_2 is not chemically active, regional and seasonal variability is caused by sources, sinks, and transport



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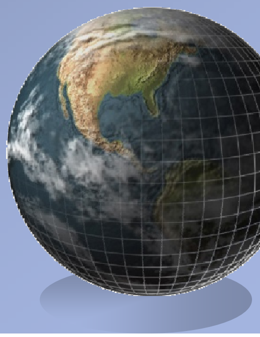


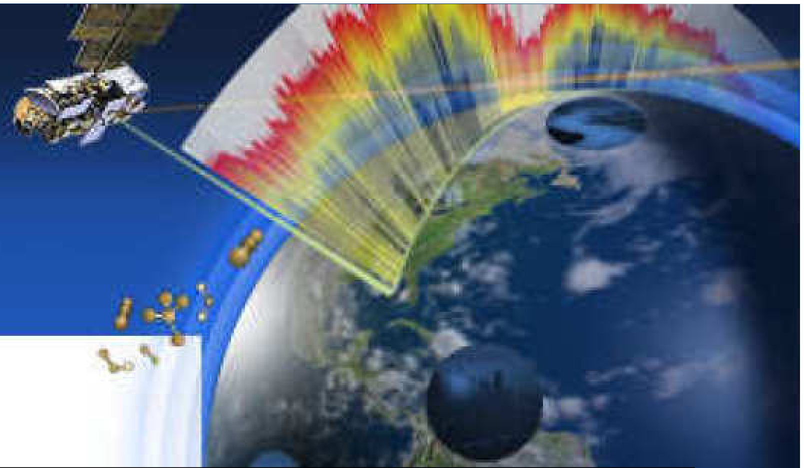
Instrument characteristics @700 cm^{-1}

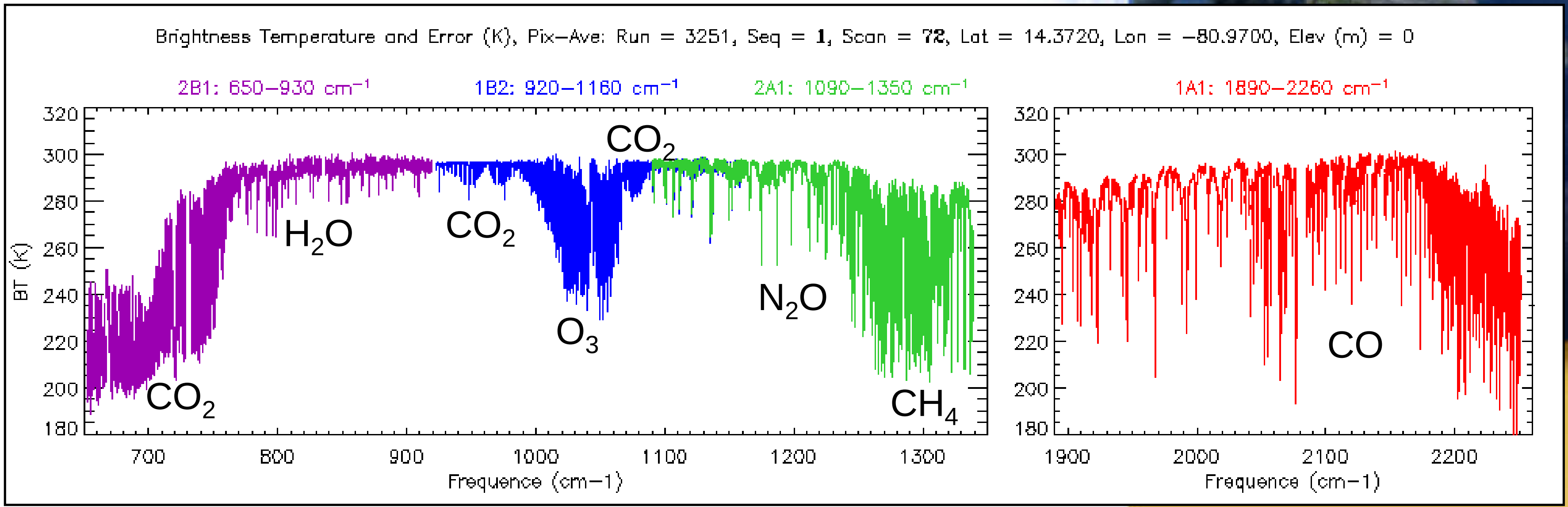
Instrument	Native resolution	S/N @ 0.5 cm^{-1}
AIRS	0.5 cm^{-1}	~525* (9 ave)
IASI	0.5 cm^{-1}	~225**
GOSAT	0.2 cm^{-1}	>475***
TES	0.1 cm^{-1}	~200****

TES CO_2 retrievals also use the “laser bands” which have 720 SNR

* http://airs.jpl.nasa.gov/technology/specifications/ with 0.35K @ 250K; 9 footprint ave
** Crevoisier et al., 2009 0.22K error at 700 cm-1
*** http://www.jaxa.jp/press/2009/02/20090209_ibuki_e.html, infrared band average
**** Shephard et al., 2008 table 2, with 0.3K @250K at AIRS resolution.

The Tropospheric Emission Spectrometer (TES) 2004-present





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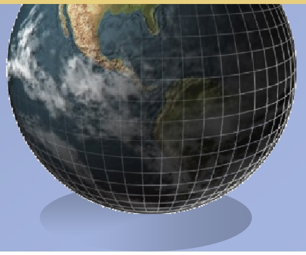
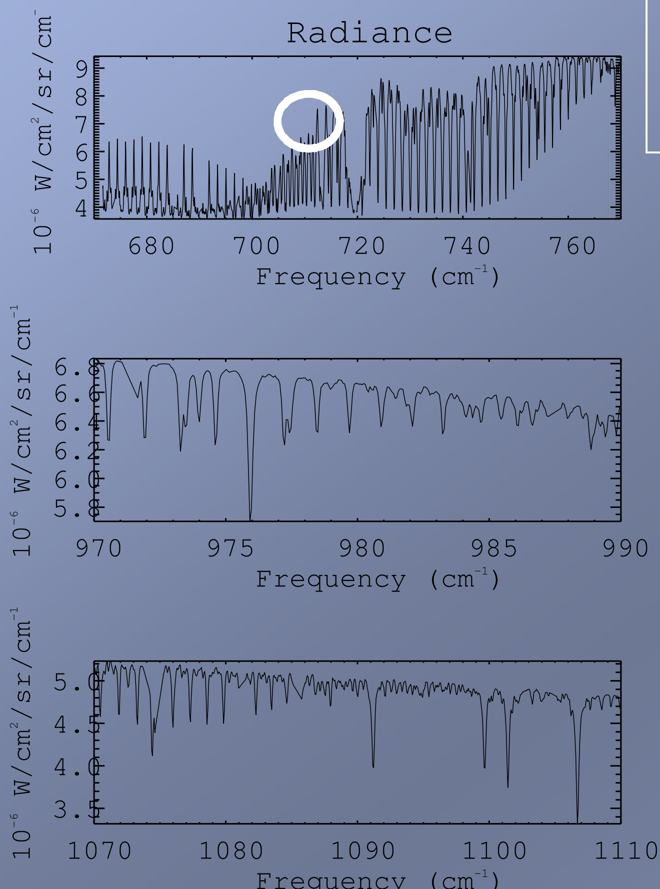
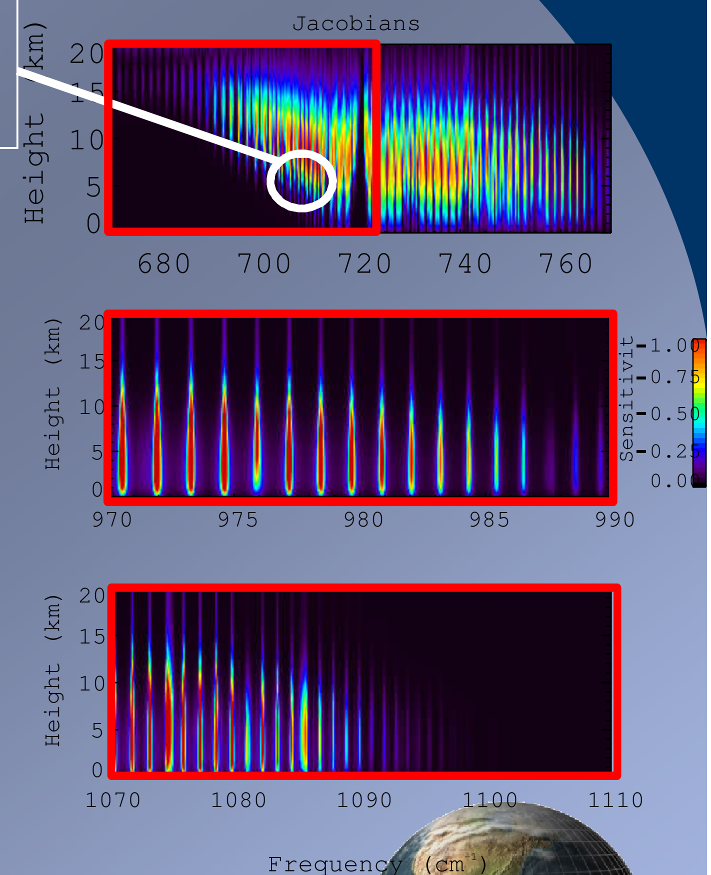
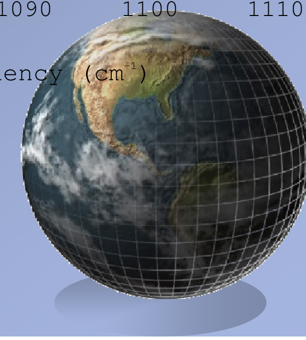


Information at infrared wavelengths



change in radiance at 710 cm^{-1} when CO_2 at 5 km is changed (normalized by spectral noise)





Jacobian[ν,z] = d(Radiance[ν]) / dln(CO_2[z]) / radiance_noise[ν]

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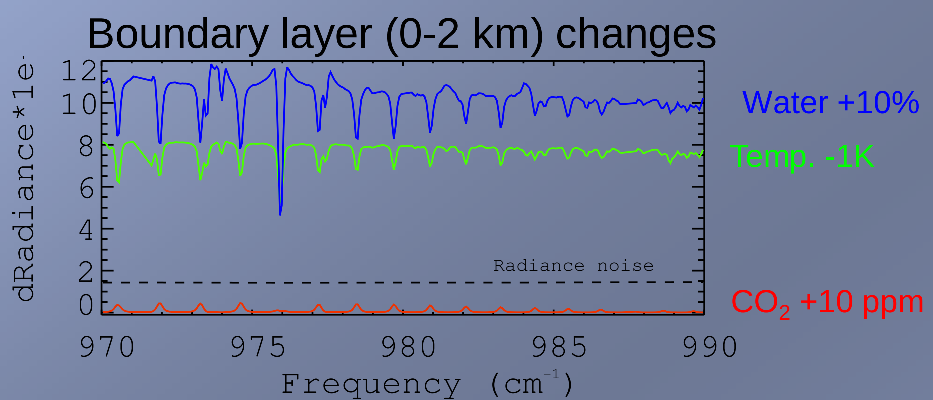
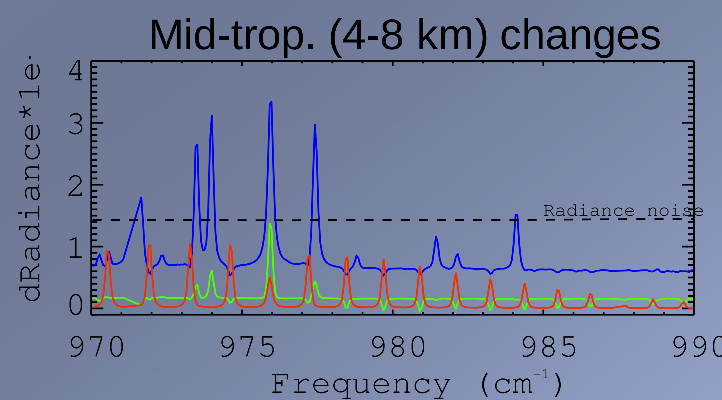
Errors in CO_2 estimates strongly depend on the accuracy of temperature and water vapor

Change in TES calculated radiance for a high thermal contrast case:





We find that 1K temperature bias propagates into a 25 ppm CO_2 bias

Retrieval approach

- Based on the optimal estimation framework (Rodgers, 2000), temperature, H_2O, CO_2, cloud and surface parameters are jointly retrieved

$$C(\mathbf{x}) = \left\| \mathbf{y} - \mathbf{F}(\mathbf{x}) \right\|^2_{\mathbf{S}_n^{-1}} + \left\| \mathbf{x} - \mathbf{x}_a \right\|^2_{\mathbf{S}_a^{-1}}$$

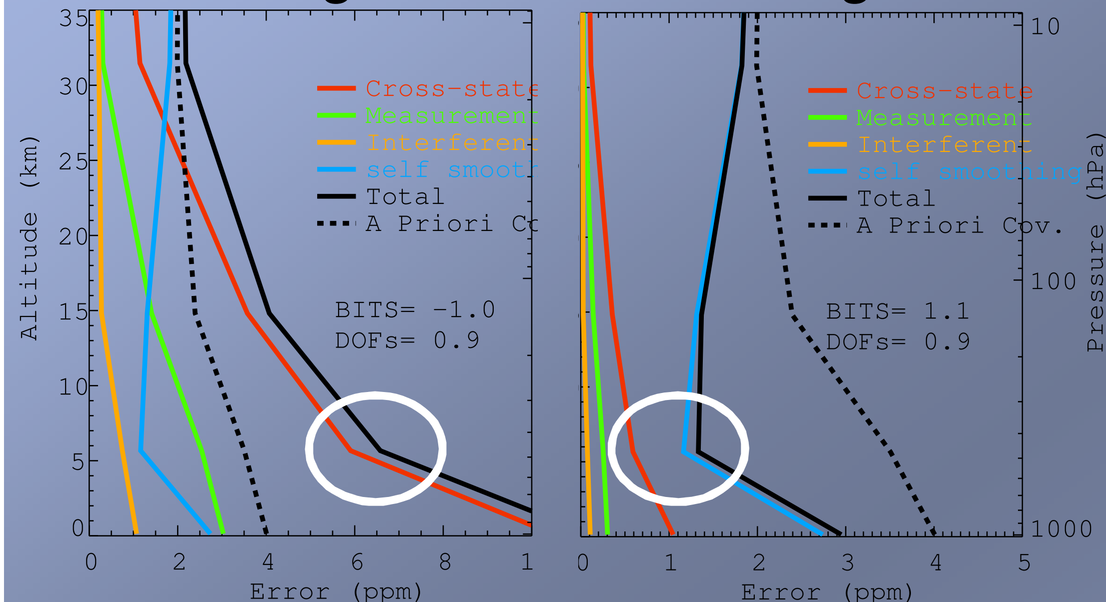
- Optimal estimation framework provides a characterization of CO_2 estimates in terms of the errors and sensitivity (Bowman, 2006; Worden, 2004):

$$\mathbf{x_{est}} = \mathbf{x_a} + \mathbf{G\varepsilon} + \mathbf{A}(\mathbf{x}_{true} - \mathbf{x_a}) + \mathbf{GK_b}(\mathbf{b_{true}} - \mathbf{b_{est}})$$

- Joint temperature, H_2O, CO_2 retrievals
  - Minimizes temperature, water bias in carbon dioxide
- Choice of windows
  - Choose broad set of windows in $\nu 2$ and laser bands
  - Remove spectral areas that are not well fit
- Constraints based on altitude-dependent Tikhonov (Kulawik et al. 2006)
  - Use 6% variability near surface and 2% higher

TES predicted and actual errors

1 target *100 targets*



1 target: ~7 ppm error

T_{atm} error is dominant

100 target: ~1.3 ppm error

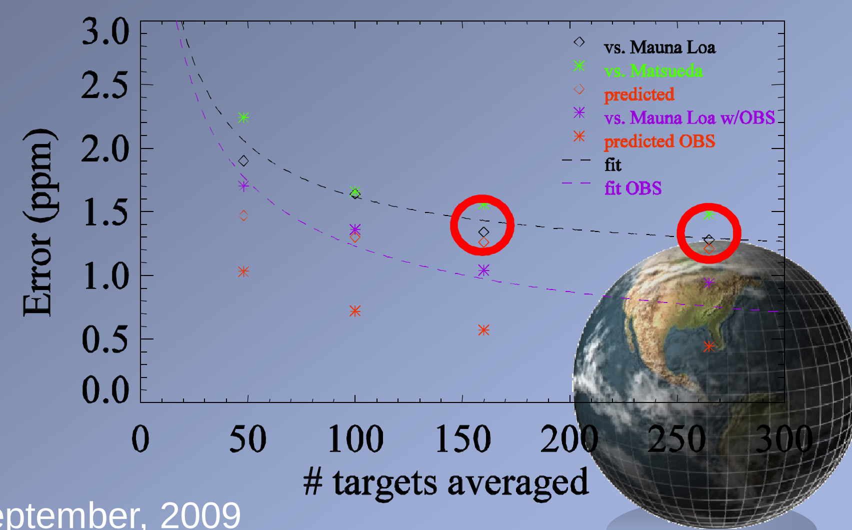
Smoothing error is dominant

1 target:

$$\mathbf{S}_{total} = \mathbf{S}_{smooth} + \mathbf{S}_{meas} + \mathbf{S}_{cross-state}$$

100 targets:

$$\mathbf{S}_{total} = \mathbf{S}_{smooth} + (\mathbf{S}_{meas} + \mathbf{S}_{cross-state})/100$$



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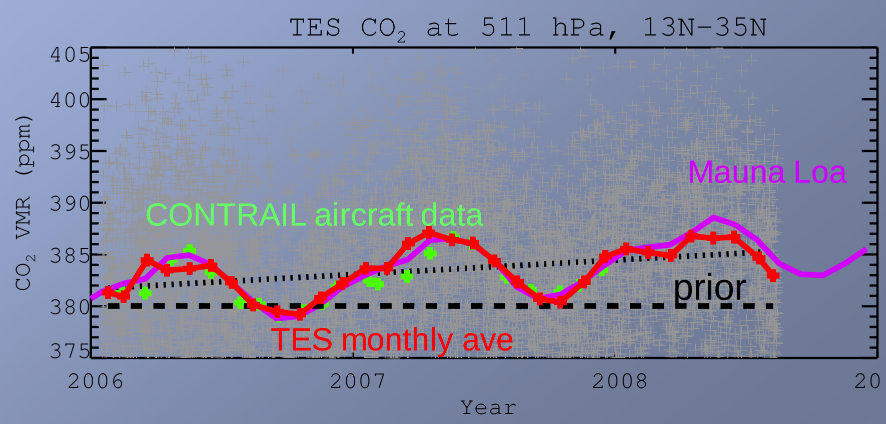
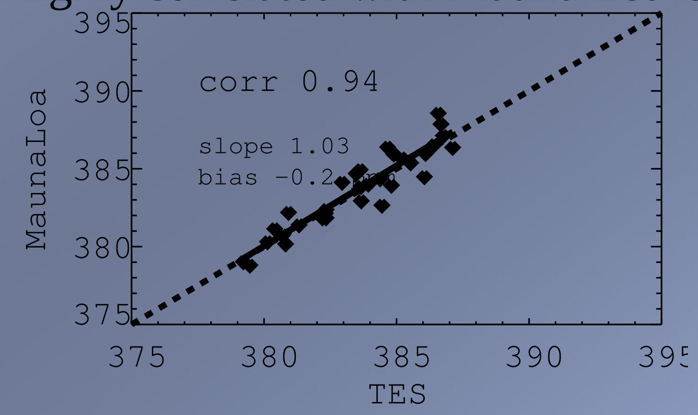
Tropospheric Emission Spectrometer CO_2

Observed yearly and seasonal variations consistent w/ in situ data



Highly correlated with Mauna Loa CO_2



Monthly averages of ~200 targets @ 5 km (511 hPa)

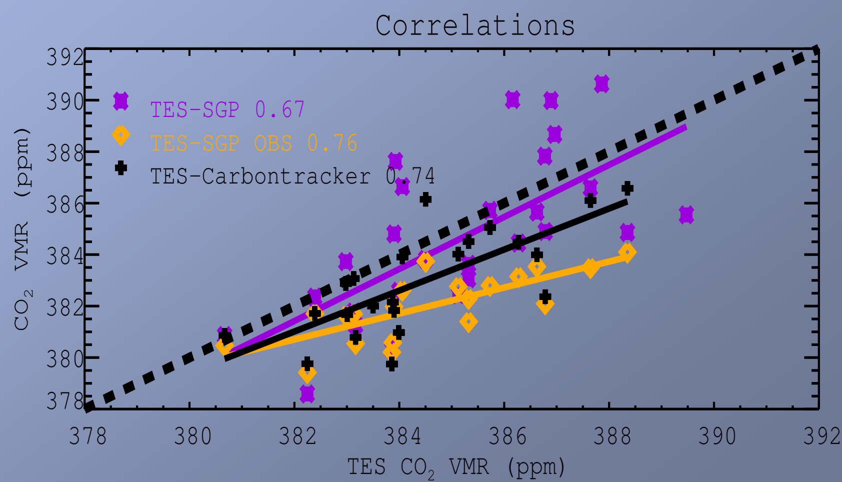
Monthly mean error is 1.5 ppm

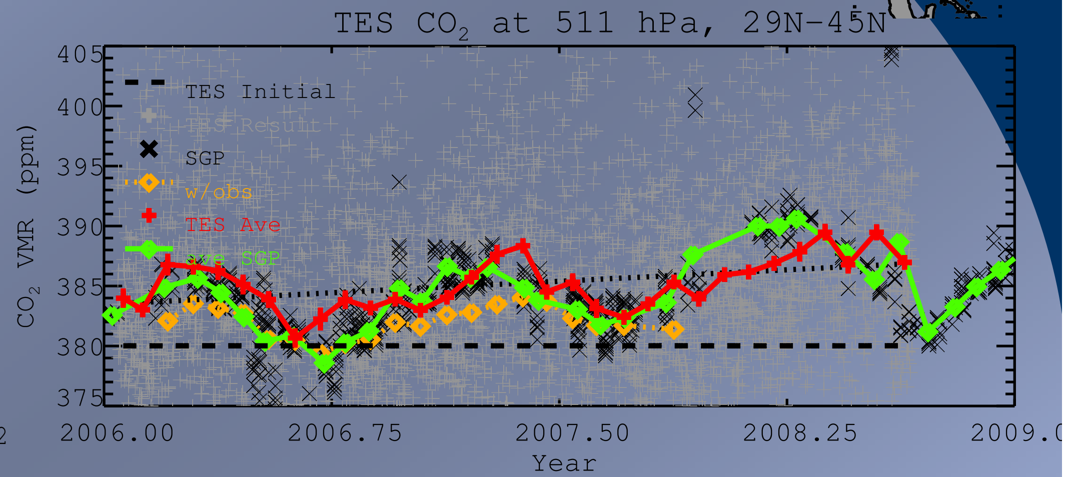
2.1% spectroscopic bias correction

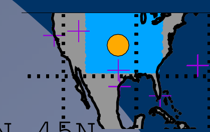
Bias close to estimated spectroscopic error of 1% (Devi, 2003)

Comparisons to SGP Aircraft CO_2

Land retrievals more challenging *and* CO_2 varies more







Correlation of TES @5 km to:

- aircraft data 2-7 km 0.7 (reasonable agreement)
- aircraft data 0-2 km 0.3 (→surface CO_2 different)

Bias: 0.55 ppm

Sensitivity: 0.63 DOF, less than Mauna Loa area due to overall lower Tsurf

SGP data were obtained from the Atmospheric Radiation Measurement (ARM) Program sponsored by the U.S. Department of Energy, Office of Science, Office of Biological and Environmental Research, Climate and Environmental Sciences Division. Contact: Margaret Torn, Lead Scientist

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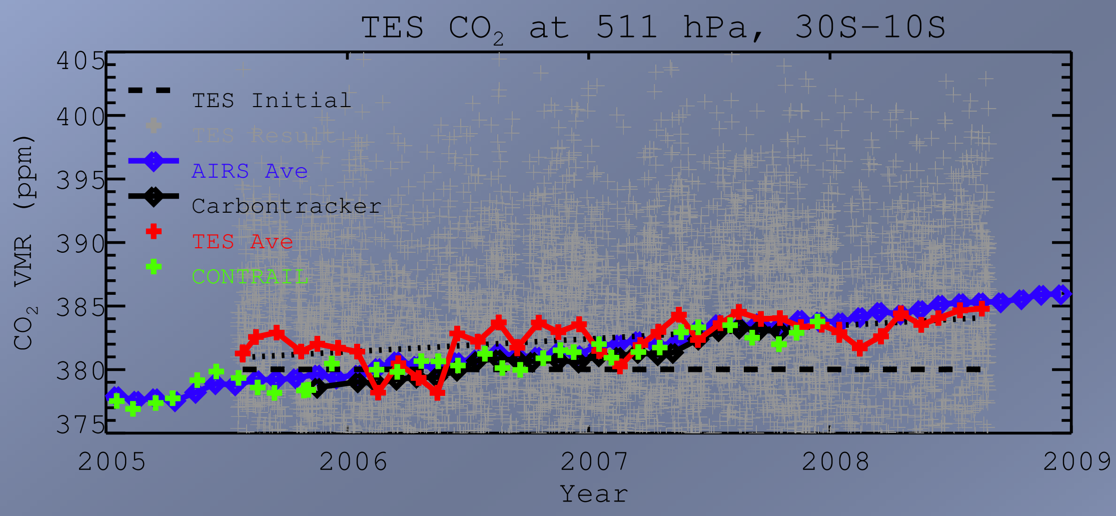
Southern hemisphere ocean

Less seasonal cycle, lower correlation w/ in situ data



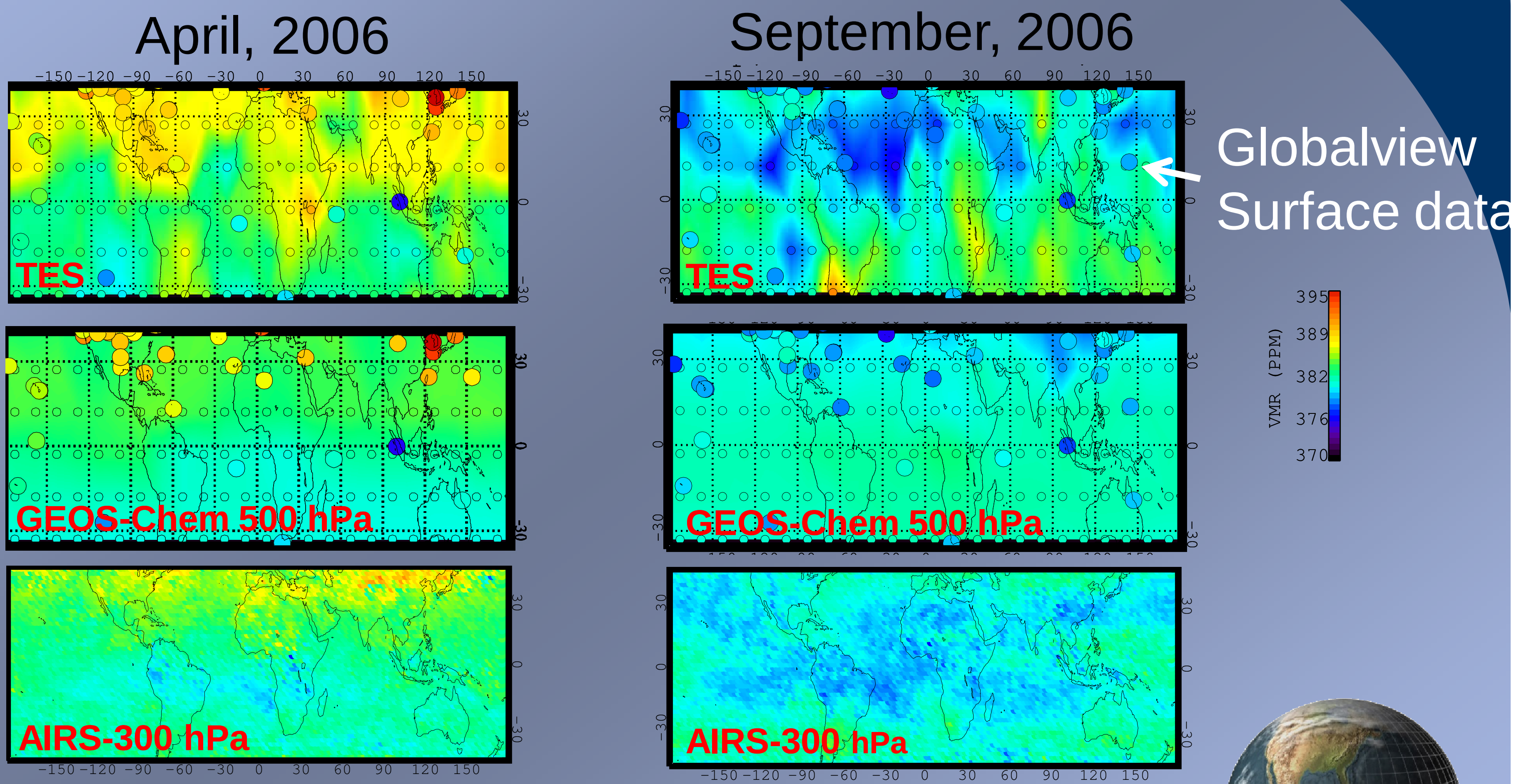
Correlation of TES @5 km to:

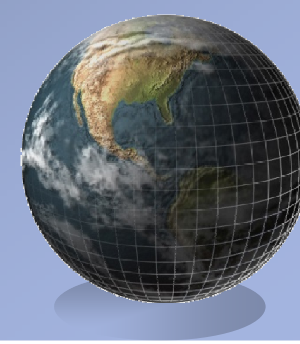
- Samoa ground station 0.39
- CONTRAIL 10 km: 0.44

Bias: 1.0 ppm

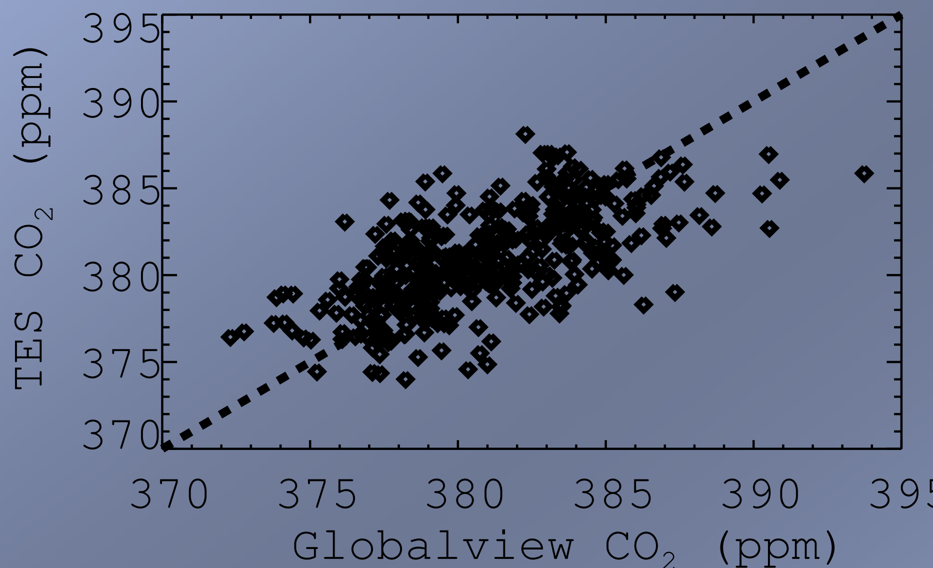
Sensitivity: 0.8 DOF

Comparisons to GEOS-Chem, AIRS, Globalview



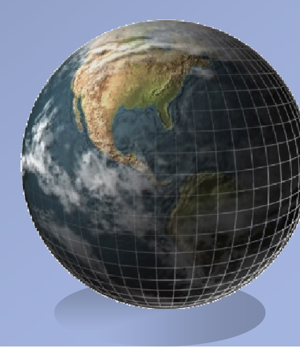


TES versus Globalview



- 0.63 correlation with Globalview for ocean sites
  - Correlation decreases if TES shifted in latitude, longitude, or time relative to Globalview

	Time (± 1 month)	Latitude (±15º)	Longitude (±30º)
TES + shift	0.58	0.51	0.50
Aligned	0.63	0.63	0.63
TES - shift	0.48	0.51	0.56



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Observing System Simulation Experiment (OSSE)

Model w/ true CO_2 fluxes

Model w/ a priori CO_2 fluxes

→ "True" model CO_2 sampled w/ TES locations, error & sensitivity

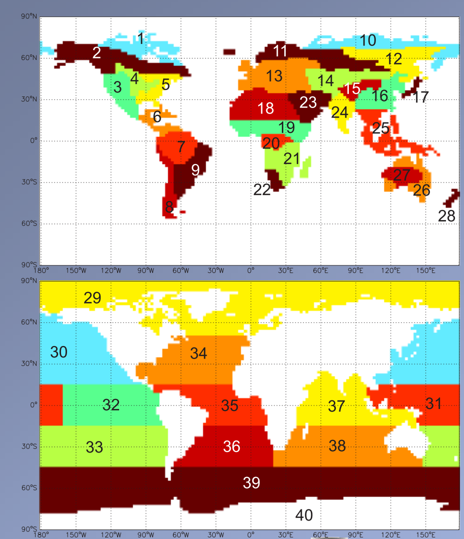
→ Minimize model-data difference → Flux Estimates

MODEL:

- GEOS-Chem with NASA GMAO met fields
- Biofuel, Fossil Fuel & Biomass Burning emissions inventories
- Climatological Terrestrial and Ocean uptake/emission
- 40 terrestrial/ocean flux regions with CO_2 sensitivities tagged

OSSE inversion:

- What is the optimal averaging size for TES?
- Simulated TES data averaged at 10°x10°, 15°x15° and 20°x30°
- Not much difference between the different binning



Work by Nassar et al. funded by Natural Sciences and Engineering Research Council (NSERC) of Canada

Conclusions for TES CO_2

Observed yearly and seasonal variations are consistent with in situ data

Errors are ~1.5 ppm for monthly averages between 40S and 40N

Averaging of 10x10 to 20x30 degrees gives similar results when used for flux estimates

Next steps

Using real TES data for source and sink estimates (see next talk!)

More validation (NH Atlantic, SH Pacific @ 3-7 km)

Improve bias characterization

Work at JPL was carried out under contract to NASA with funds from ROSES 2007. Work by Nassar et al. funded by Natural Sciences and Engineering Research Council (NSERC) of Canada. We acknowledge use of GLOBALVIEW-CO_2 and Mauna Loa from NOAA-ESRL and CONTRAIL data from World Data Centre for Greenhouse Gases (*WDCGG*). CarbonTracker 2008 results provided by NOAA ESRL, Boulder, Colorado, USA from the website at http://carbontracker.noaa.gov

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Thanks to H. Worden for S/N calculation help

References

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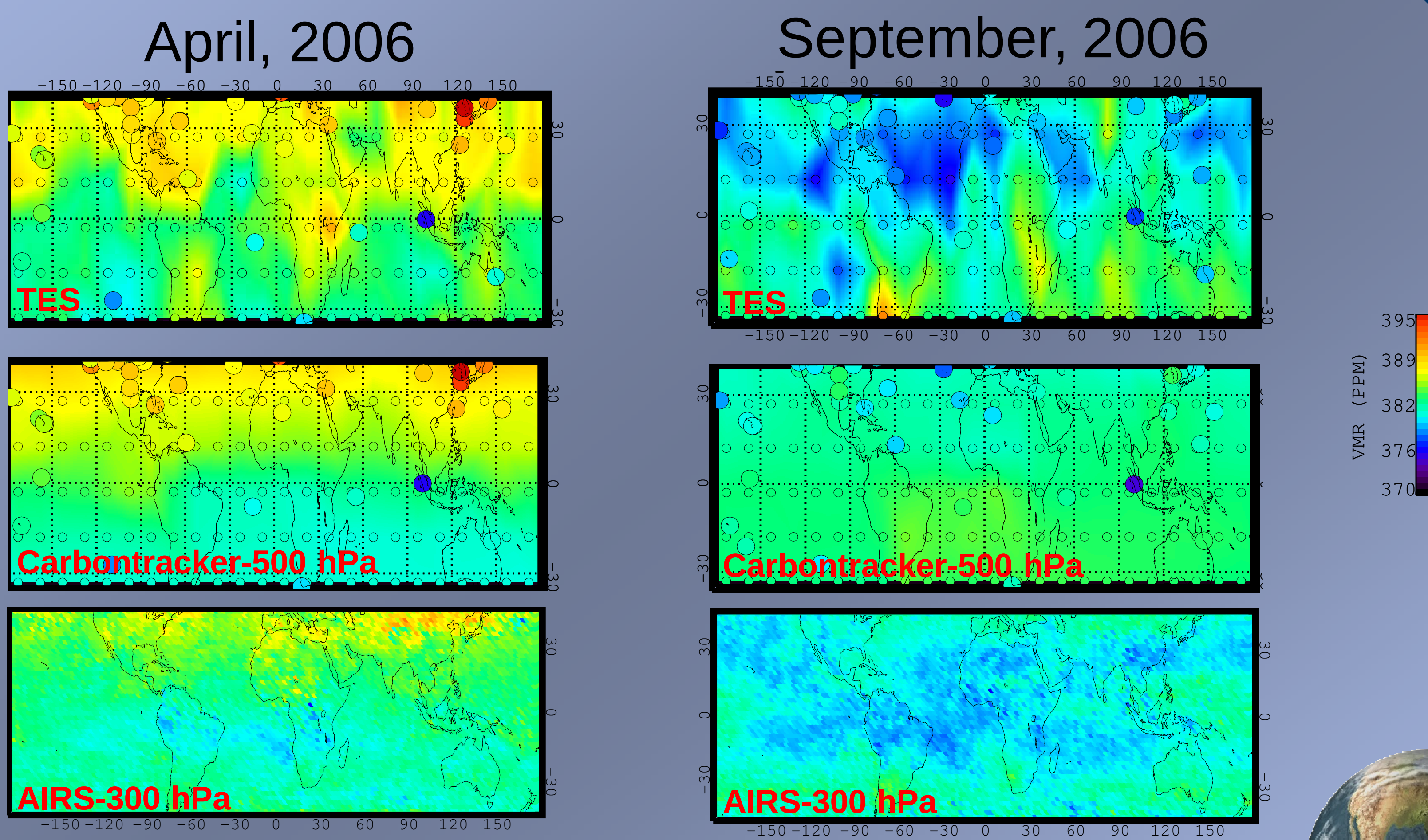
U.S. Department of Commerce | National Oceanic and Atmospheric Administration Earth System Research Laboratory | Global Monitoring Division http://www.esrl.noaa.gov/gmd/dv/site/SMO.html

Comparisons to Carbontracker, AIRS, Globalview



CarbonTracker 2008 results provided by NOAA ESRL, Boulder, Colorado, USA from the website at http://carbontracker.noaa.gov

Resolution versus error tradeoff

Averaging area	# per bin	observation error
10 x 10 degree x 1 month	45	2.0 ppm
15 x 15 degree x 1 month	91	1.4 ppm
20 x 30 degree x 1 month	222	1.0 ppm

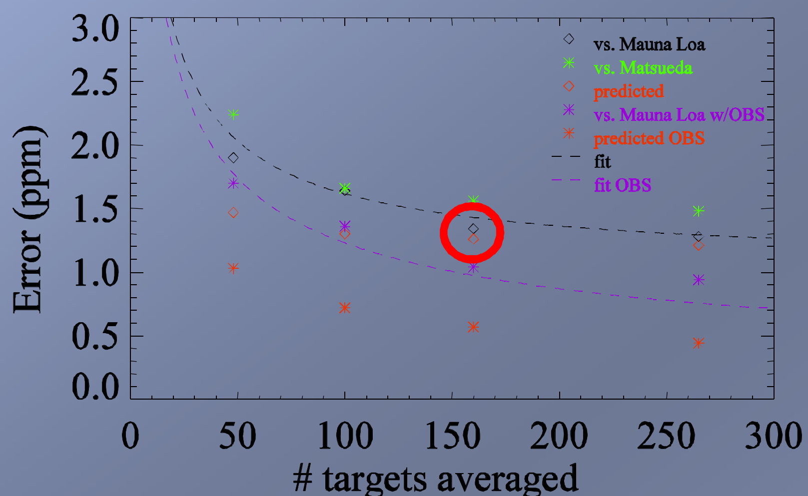
OSSE results

	10x10	15x15	20x30
Land mean error reduction	0.72	0.74	0.74
Ocean mean error reduction	0.87	0.87	0.88
DOFs	14.9	13.9	13.7

$$\sqrt{\mathbf{S}_x / \mathbf{S}_a}$$

Results are comparable between the 3 averaging sizes with 10x10 giving the largest reduction in flux uncertainty; however all three results give similar results. The different cases do better for different locations.

TES actual errors



- Compare TES to Mauna Loa and CONTRAIL CO_2
- Averaging decreases error
- Progression agrees with 1/sqrt(N) reduction in error